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Signal Processing Results for Continental Aperture Seismic Array

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts

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LINCOLN LABORATORY

SIGNAL PROCESSING RESULTS FOR CONTINENTAL APERTURE SEISMIC ARRAY

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Group 22

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ABSTRACT

The processing of short-period P-wave data from a continental aperture seismic array is considered. The array consists of sites located at the Large Aperture Seismic Array (LASA) in eastern Montana and Long Range Seismic Measurement (LRSM) stations located in North America. In particular, the feasibility of recognizing the arrival of the pP phase, making use of P-pP differences in velocity across such a large array, is considered. In addition, the determination of the P-wave source structure of an event is considered by using the array to essentially steer many beams in the vicinity of the epicenter of the event. The capability of the array to perform these two functions is evaluated and discussed in detail.

Accepted for the Air Force
Franklin C. Hudson
Chief, Lincoln Laboratory Office

I. INTRODUCTION

It has been found, using data from the Large Aperture Seismic Array (LASA) in eastern Montana, that valuable discriminants can be based on the use of the spectral ratio for the P-wave, and the relation between surface-wave and body-wave magnitude, M_s-m_b. A recent experiment[1] has determined the effectiveness of the LASA to discriminate between earthquakes and underground nuclear explosions using these two, as well as other, discriminants based on results obtained from a large population of events. However, these two discriminants are not useful at LASA below a certain magnitude threshold. It is not clear that the spectral ratio defined for LASA data will provide effective discrimination results when obtained at other stations. This statement is based on preliminary data from sites other than LASA. It is possible to use the M_s-m_b discriminant effectively at other stations. However, the utility of this discriminant is limited by the difficulty in detecting the Rayleigh surface wave due to the poor signal-to-noise ratio on the long-period instruments,[2] as compared to that on the short-period sensors. Thus, in attempting to lower the identification threshold by using world-wide observations, it is desirable to utilize discriminants other than those based on the spectral ratio and M_s-m_b.

One effective way of lowering the identification level is to use discriminants based solely on the characteristics of the P-wave, due to the high signal-to-noise ratio on the short-period seismometer. The purpose of the present work is to investigate such discriminants using data from LASA, and Long Range Seismic Measurement (LRSM) sites located in North America. In particular, a depth discriminant based on the detection of pP will be considered. In addition, the P-wave source struc-

ture of the event will also be considered. In order to accomplish both of these objectives, it will be necessary to perform delay-and-sum processing, or beamforming, of short-period P-wave data. These data are obtained from sites located within an aperture of continental dimension, usually about 4000 km.

An extensive investigation has been made of beamforming of short-period P-wave data at LASA.[3] It was found that the performance of the beamforming process was degraded due to the distortions introduced in the P-waves at LASA because of inhomogeneities in crustal structure at both the receiver and the source. It is also possible that inhomogeneities in the earth's mantle may exist which contribute to the distortion of the P-wave. It would be expected that these effects would be even more severe for P-waves observed over a continental aperture which is much larger than that of LASA, i.e., 4000 km as contrasted with 200 km. This was indeed found to be the case, so that beamforming over continental apertures does not appear to yield meaningful results. This will be discussed in greater detail subsequently.

II. DESCRIPTION OF CONTINENTAL ARRAY

The continental array considered consisted of sensors located at LRSM sites in North America and at LASA. In reality, the subarray straight sums at LASA were employed since this has the effect of improving the signal-to-noise ratio of the short-period P-wave data. The site designations and coordinates are given in Table I. A map which shows the locations of the sites is presented in Fig. 1.

The response of the short-period seismograph system which is typical of that used at the LRSM stations is shown in Fig. 2. This response corresponds to that of either a large or small Benioff short-period seismometer. The response of the short-period seismometers used at LASA is slightly different than that given in Fig. 2, and in the subsequent analysis will be considered to be the same as that for the LRSM sites. The calibration data for the sensors at both LASA and the LRSM sites were available so that it was possible to weight the data so as to maintain a uniform calibration level across the continental aperture seismic array.

The data from the LRSM sites was available only on FM analog magnetic tape. Thus, it was necessary to digitize the data employing an analog-to-digital converter, using 14 bit quantization with one bit for the sign of the amplitude of the data. These digitized data were then merged with the LASA data which were already available in a digital format on magnetic tape. The resultant tape was then in a format which could be read directly on the IBM 360/65 using available computer programs.

TABLE I

LIST OF STATIONS

SITE	SITE DESIGNATION	SITE COORDINATES LATITUDE (DEG. NORTH) D	M	S	LONGITUDE (DEG. WEST) D	M	S
AX2AL	Alexander City, Alabama	32	46	38	86	07	48
BEFL	Belleview, Florida	28	54	19	82	03	52
FKCO	Franktown, Colorado	39	35	12	104	27	42
HL2ID	Hailey, Idaho	43	33	40	114	25	08
HNME	Houlton, Maine	46	09	43	67	59	09
KCMO	Kansas City, Missouri	39	21	21	94	40	17
KNUT	Kanab, Utah	37	01	22	112	49	39
LAAO	LASA, Montana	46	41	19	106	13	17
LAF1	LASA, Montana	47	22	17	105	11	12
LAF2	LASA, Montana	45	54	35	105	29	14
LAF3	LASA, Montana	45	58	21	107	04	45
LAF4	LASA, Montana	47	24	37	106	56	53
LCNM	Las Cruces, New Mexico	32	24	08	106	35	58
MNNV	Mina, Nevada	38	26	10	118	08	53
MOID	Mountain Home, Idaho	43	04	19	116	15	56
NPNT	Mould Bay, Northwest Territories	76	15	08	119	22	18
PGBC	Prince George, British Columbia	53	59	50	122	31	23
SV3QB	Schefferville, Quebec	54	48	39	66	45	00
RKON	Red Lake, Ontario	50	50	20	93	40	20
WH2YK	Whitehorse, Yukon Territory	60	41	41	134	58	02

III. DISCUSSION OF COMPUTATION METHODS

We now describe the methods which were used to determine depth and P-wave source structure using data from a continental aperture seismic array. The data from each sensor in the array were prefiltered with a bandpass filter whose frequency response is shown in Fig. 3a. The corresponding impulse response of the filter is given in Fig. 3b and the response of the filter to a step of sine wave of frequency 1 Hz is shown in Fig. 3c. The data were sampled at a frequency of 20 Hz and the waveform used at each site was 102.4 seconds long, yielding 2048 samples. The fast Fourier transform was employed to transform the data sequence into the frequency domain and the frequency response shown in Fig. 3a was applied directly in this domain. The filtered data were then obtained by transforming the result. The 3-db response frequencies of the filter are 0.64 Hz and 2.3 Hz, which corresponds to the frequency band in which most of the P-wave energy lies. It should be noted that the filter is phaseless in the sense that no phase distortion is introduced. This particular filter was chosen because it produced very little distortion in the data. There is a small precursor which is introduced as seen from Fig. 3c. However, an analyst usually aligns the traces so that this precursor is not included in the processing of the data. In Fig. 3c we see that very little distortion is introduced after about one second from the onset time of the sine wave.

The purpose of the continental aperture seismic array computer program is to determine the depth of an event by recognizing the arrival of the pP phase, making use of P-pP differences in velocity, and to determine the P-wave source structure of the event by essentially steering many beams in the vicinity of the epicenter of the event. The data consist of the digitized and merged records from LASA and LRSM sites

located in North America, as mentioned previously.

The program operates by assuming that the epicenter, but not the depth, of the event is known, as well as the P-wave arrival times at all the stations in the continental array. These times are computed from travel time tables, using the known station locations and the event epicenter. The P-waves at the various stations are brought into time alignment by an analyst. All beamforming operations are done on the aligned traces and the time delays used are computed from travel time tables, relative to the previously computed P-wave arrival times. This procedure is used in the hope that the need for using station corrections is eliminated. Amplitude weights are employed and are determined by using the calibration data for the stations, and by compensating for the different P-wave attenuation caused by the different distances of the stations to the epicenter.

The presence of the pP phase is determined by performing a beamforming operation over the network stations at successive times and with proper interstation delays corresponding to trial depths ranging from 10 to 200 km. The power of the beam output over the appropriate 1-second interval is computed as a function of the trial depth and the trial depth that corresponds to the peak of these powers is then taken as an estimate for the true depth.

The computed, or possibly known, value of depth is used in the determination of the P-wave structure of the source. A beamforming operation over successive 2-second intervals, starting with the P-arrival time, is performed. This results in a plot of power vs various latitudes and longitudes about the source hypocenter at the computed depth, with one contour plot for each 2-second interval. A theoretical network beam pattern is also computed and plotted in a similar manner to pro-

vide a basis for comparison with the experimental results.

Several experiments were performed to determine the validity of the results obtained using the computer program. These results will now be described. One of the experiments dealt with the effect of power level changes as a function of time, for the seismic data. In this experiment an exponentially damped sinusoid, whose frequency was 1 Hz, was generated at a number of stations. The stations used were the same as those to be discussed subsequently in the processing of the 27 October 1966 Novaya Zemlya event. The waveforms at all of the stations were made to be identical, indicating that the data were being generated by a stationary source located at a fixed point on the earth which was taken to be the epicenter for the previously-mentioned event. Thus, when the beamforming process is performed over successive two-second intervals of data, the location of the peak of the output beam power should remain stationary at the assumed epicenter.

However, it was found that the location of this peak did not remain stationary, but shifted by a considerable amount. This shift of position was due to power level variations along the waveform. In other words, it is possible that, when two-second segments of the waveform at each sensor are shifted using time delays corresponding to a source location other than the epicenter, the decrease in beam power output due to the misalignment of the traces is more than compensated for by the increase in power level in each of the waveforms. This effect, due to power level variations, is undesirable and should be removed, since otherwise there would be very little credence placed in the source structure computation.

In order to remove this effect, compensation for power level variations was employed in the beamforming process. This was accomplished by measuring beam

power output as

$$P_i = \sum_{k=1}^{M} \left(\sum_{j=1}^{N} W_{j,i} D_{j,k+t_{ji}} \right)^2$$

where

$$W_{j,i}^2 = \sum_{k=1}^{M} D_{j,k+t_{ji}}^2$$

and $D_{j,k}$ is the data in the j^{th} sensor at the k^{th} time sample, t_{ji} is the time delay required in the j^{th} sensor for the i^{th} source location, N is the number of sensors and M is the number of data samples contained within the integration time of two seconds, which for 20 samples per second would be equal to 40. In the previous beamforming operation where no power compensation was used, the preceding formula applies with $W_{j,i} = 1$. In essence, this weighted beamforming operation is measuring the coherence of the delayed waveforms and is relatively immune to power level variations. When this beamforming operation was applied to the artifically generated data mentioned previously, the location of the peak power output remained stationary as was desired.

Another experiment was performed to test the validity of the P-wave source structure computation using the weighted beamforming operation which compensates for power level variations. In this experiment four source locations were assumed at the points X, A, B, C, as shown in Fig. 4. The point X corresponded to the location of the epicenter for the 27 October 1966 Novaya Zemlya event, to be discussed subsequently. A pulse is assumed to propagate from a given source location (point X, A, B, or C), to each sensor in the array, which is the same as that discussed previously, with a travel time determined

by the time required for a compressional wave to propagate from point X to the given source location plus the time required for a P-wave to travel from the given source location to the sensor. This latter time is determined from travel time tables by using the distance from the given source location to the sensor. The time required for a compressional wave to propagate from point X to a given source location is equal to the distance between these points, in km, divided by 6 km/sec. The amplitudes of the pulses from X, A, B, C were assumed to be 1, $\sqrt{2}/2$, 1/2, $\sqrt{2}/4$, respectively, corresponding to successive 3-dB increments in power level. This sequence of four pulses at each sensor was applied to the bandpass filter described previously to make the data look somewhat like actual observed seismic data.

The results of the source structure computation are shown in Fig. 4, which shows contours of $-10 \log (P_i/P_{max})$, where P_{max} is the maximum value of P_i. The level of the contours varies from 0 to 3 dB in increments of 1 dB. A grid of $\pm 1^\circ$ in distance is given about the epicenter, located at the point marked X, and the power is computed at 21 x 21, or 441, points. The results are presented only for four two-second intervals, or a total of eight seconds, following the onset time of the P-wave. The dotted contour surrounding the epicenter, marked X, in Fig. 4 indicates the locus of points of possible sources of scattered P-waves. The results shown in Fig. 4 indicate that the location of the peak power output shifts by an amount which is in reasonably close agreement with the known shift in location of the source of the P-waves. That is, the location of the zero in this figure shifts successively from point X to A, to B, and then to C. Thus, a reasonably accurate computation of source structure has been obtained.

A more stringent test of the method was performed by assuming a shift of

source location in two opposite directions simultaneously, instead of a shift in a single direction as was done previously. In this case, the shift in the location of the peak output power was unable to follow the shift in location of the source. Thus, it would appear that the source structure computation is useful only in those situations where the source location is moving in a single direction. The weighted beamforming operation was also employed in the depth computation, in a manner similar to that used in the P-wave source structure computation.

It was found that there were very significant differences in waveshape at each station. These differences are believed to be caused by the complex crustal structure at each site, as well as at the source. An attempt was made to design equalization filters which would compensate for the distortion in waveshape introduced by crustal structure. However, these attempts produced results which were believed to be largely unsuccessful and thus will not be presented. Hence, it appears to be impractical, at the present time, to remove the effects introduced by crustal in-homogeneities.

IV. RESULTS FOR DEPTH AND P-WAVE SOURCE STRUCTURE COMPUTATION

We now present the results obtained by using the continental aperture seismic array computer program to process the data from eight events. The parameters for the events considered are given in Table II. These events consist of three presumed underground nuclear explosions from Novaya Zemlya, one presumed underground nuclear explosion from Eastern Kazakh and four earthquakes. The earthquakes were chosen on the basis that at least four stations, not necessarily any of those used in the processing of the event, reported the presence of a pP phase for it to the U. S. C. G. S. The epicenters for the eight events are also located on the map in Fig. 1.

The bandpass filtered waveforms, as well as the results of the P-wave source structure computation, for the eight events are displayed in Figs. 5 through 20. It is also possible to determine the sites which were employed, for a particular event, from these figures. These sites are displayed in order of increasing distance from the epicenter. The display of the results for the P-wave source structure computation is similar to that in Fig. 4. A typical example of a theoretical network beam pattern at 1 Hz is shown in Fig. 21. This beam pattern applies to the collection of sensors which was used in the processing of the 27 October 1966 Novaya Zemlya event, and shows that typically a resolution of about 0.2°, or about 20 km, is achieved with a continental aperture seismic array. The beam pattern is obtained by computing the power at the i-th position, corresponding to a given latitude and longitude in Fig. 21, as

$$P_i = \left| \frac{1}{N} \sum_{j=1}^{N} \epsilon^{i2\pi t_{ji}} \right|^2$$

where t_{ji} and N were defined previously. The power in Fig. 21 is displayed in db,

TABLE II

LIST OF EVENTS

EVENT NO.	DATE	REGION	ORIGIN TIME (GMT)	LAT. (DEG.)	LONG. (DEG.)	DEPTH (km) (CASA)	DEPTH (km) (USCGS)	m_b (USCGS)
1	27 Oct 66	Novaya Zemlya	05:57:58	73.44N	54.75 E	–	0	6.3
2	18 Dec 66	Eastern Kazakh SSR	04:57:58	49.93N	77.73E	–	0	5.9
3	9 Feb 67	Colombia	15:24:47	2.85N	74.89W	106	58	6.3
4	14 May 67	Chile-Bolivia Border Region	08:38:33	20.56S	68.92W	114	109	5.2
5	26 Sep 67	Near Coast of Central Chile	16:11:24	30.04S	71.53W	22	55	5.7
6	15 Oct 67	Near Coast of Nicaragua	08:00:50	11.86N	86.02W	80	162	6.2
7	21 Oct 67	Novaya Zemlya	04:59:58	73.37N	54.81E	–	0	5.9
8	7 Nov 68	Novaya Zemlya	10:02:05	73.41N	54.86E	–	0	6.3

relative to the maximum power of unity, in steps of 1 db from 0 to 6 db.

The results of the depth computation provided by the continental aperture seismic array (CASA) program are given in Table II, along with the depths reported by the U. S. C. G. S. The corresponding positions in time are denoted on the waveforms presented in Figs. 9, 11, 13, and 15. It is seen that in only one of the four cases considered was there agreement between the CASA program depth and the U. S. C. G. S. depth. That is, for event number 4 there is good agreement between the two depths. However, for this event the presence of the pP phase is quite clear on the individual records, cf. Fig. 11. In the other three cases the presence of the pP phase is not clear on the individual traces and the CASA program detected the presence of this phase at a time which appears to yield a depth significantly different than that reported by the U. S. C. G. S. This happened in spite of the fact that there were four stations on the earth that reported the presence of this phase to the U. S. C. G. S. Thus, it would appear that the determination of depth by detecting the presence of the pP phase with a continental aperture seismic array is relatively unreliable. This is probably due to the effects of the crustal inhomogeneities mentioned previously, as well as other effects which may not as yet be well understood.

We now consider the results for the P-wave source structure computation, and begin by considering event number 1, which is the 27 October 1966 Novaya Zemlya event. The waveforms from the various sites which were used are shown in Fig. 5. The stations are distributed over an aperture of about 4300 km and vary in distance from the epicenter from 46° to 74°. For this event, as well as the other presumed underground nuclear explosions, the determination of depth by the CASA program is not meaningful and the depth is assumed to be zero km in the P-wave source structure

computation.

The waveforms of Fig. 5 show striking differences in waveshape for this event as viewed across the network. For example, the waveforms observed at RKON, HNME are very simple while those at LASA, i.e., the subarray straight sums from LAAO, LAF1, LAF2, LAF3, LAF4, are extremely complex. These data show that some caution must be exercised in employing the complexity criterion for discrimination.

The results of the P-wave source structure computation for event number 1 are shown in Fig. 6 (a-d). The X in each figure, as well as those figures for the other events, represents the location of the epicenter provided by U.S.C.G.S. and the zero corresponds to the location from which the peak power output is provided by the weighted beamforming process. In Fig. 6a the zero and X coincide, indicating that during the first two seconds after the origin time the peak power is coming from the epicenter. In Figs. 6 (b-d) we see a migration of the location providing the peak power. These locations are indicated in Fig. 22 on a map of the Novaya Zemlya region.

The migration of the location of the zeros in Figs. 6 (b-d) is compatible with conditions imposed by known seismic compressional wave velocity in the crust. That is, the locations of the zeros lie inside the dotted contour surrounding the epicenter marked X. This dotted contour was described previously in connection with Fig. 4 and is the locus of points of possible sources of scattered P-waves during the time interval defined by the particular frame. If a point marked zero should be obtained outside of this contour then it is known immediately that an erroneous result has been obtained. Thus, some credence may be placed in the P-wave source structure computation for event number 1. However, the results for two other Novaya Zemlya

events, numbers 7 and 8, shown in Figs. 18 and 20, respectively, do not yield consistent results since in many cases the location of the zero falls outside the dotted contour. This also happens quite often with the other events, cf. Figs. 8, 10, 12, 14, 16. Thus, it appears that the determination of the P-wave source structure by means of beamforming of continental aperture seismic array data is relatively unreliable. Once again, this is probably due to the effects of both source and receiver crustal inhomogeneities which were mentioned previously, as well as other effects.

V. CONCLUSIONS

The feasibility of detecting the arrival of the pP phase has been considered, using weighted beamforming of data from a continental aperture seismic array. It was found that this procedure was relatively unreliable, probably because of the effects of crustal, and possibly mantle, inhomogeneities. This conclusion is based on only a small population of events consisting of four earthquakes. However, it appears that the conclusion is valid since it agrees with similar conclusions obtained by Chiburis and Ahner[4] on the basis of a large population of events. Thus, those previous reports which indicated promising results for processing of data from continental aperture seismic arrays to detect the presence of the pP phase should be considered as unduly optimistic.

It was also found that the determination of the P-wave source structure using weighted beamforming of data from a continental aperture seismic array was unreliable, once again due to the effects of crustal and mantle inhomogeneities. The theory of plate tectonics[5,6] holds some promise for understanding these inhomogeneities and possibly compensating for them. If this were possible then there might be some hope in obtaining meaningful results from the processing of data from sensors located over a continental aperture. In the lack of such an understanding, the beamforming of data from a continental aperture seismic array must be considered as yielding unreliable, if not meaningless, results.

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Fig. 1. Locations of stations and events.

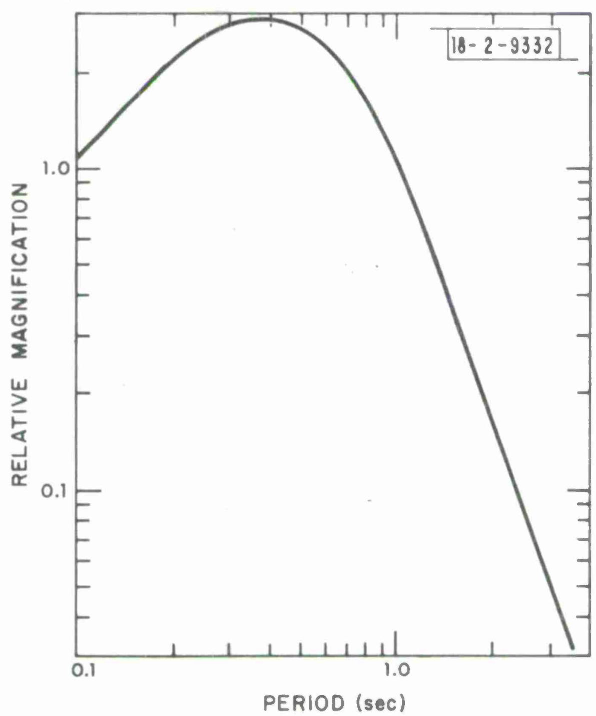

Fig. 2. Frequency response of the short-period seismometer system.

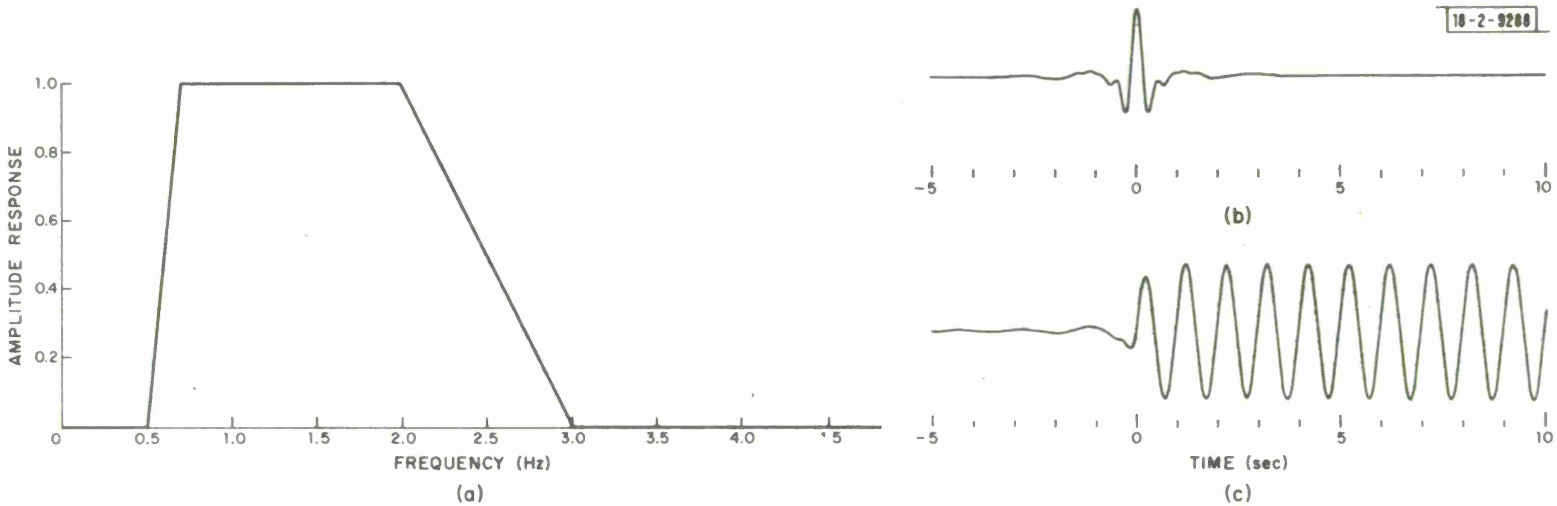

Fig. 3. Frequency response, impulse response and stepped sine wave response of bandpass filter.

Fig. 4. P-wave source structure result for artificially-generated seismic data.

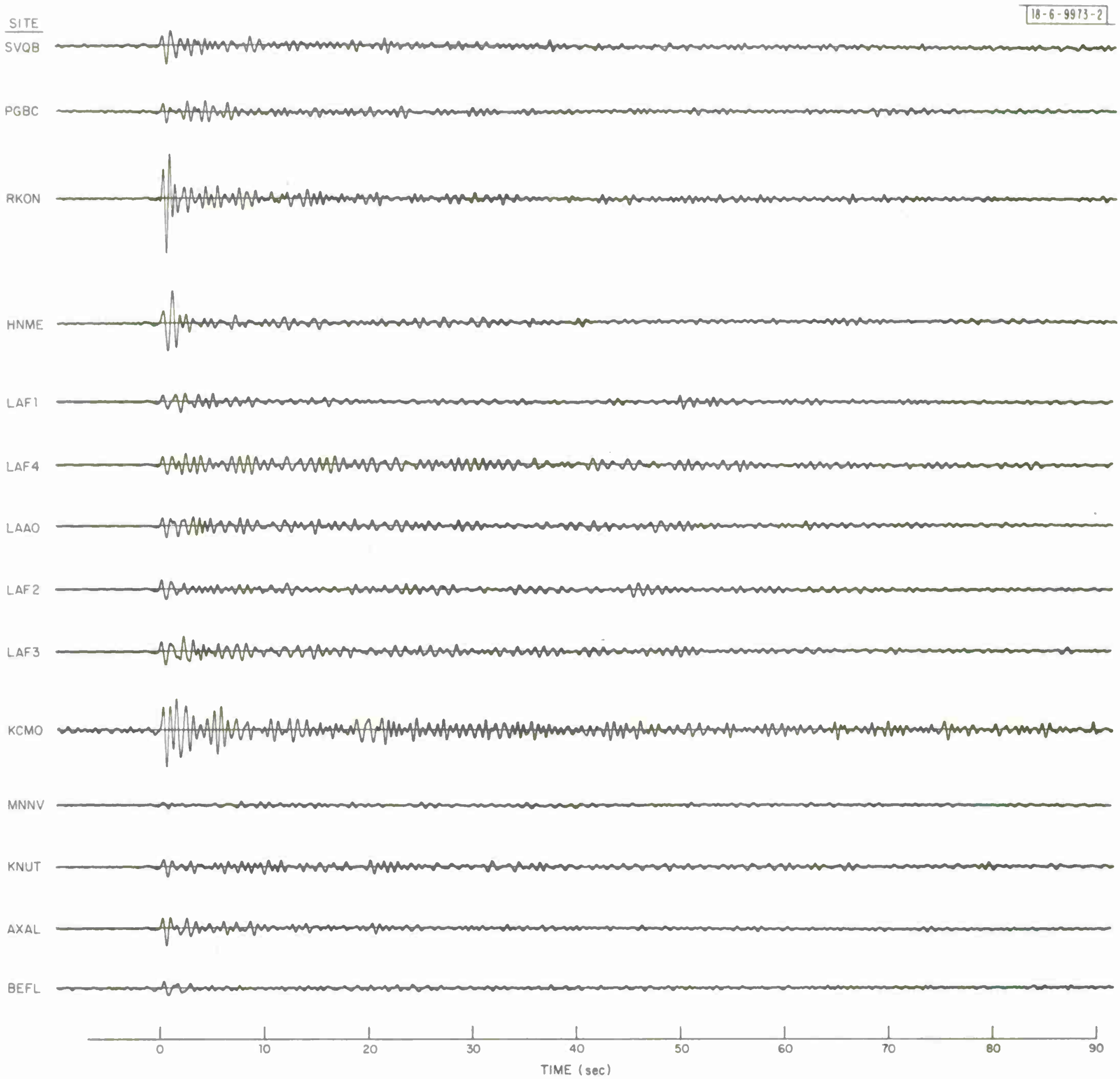

Fig. 5. Waveforms for 27 October 1966 Novaya Zemlya event.

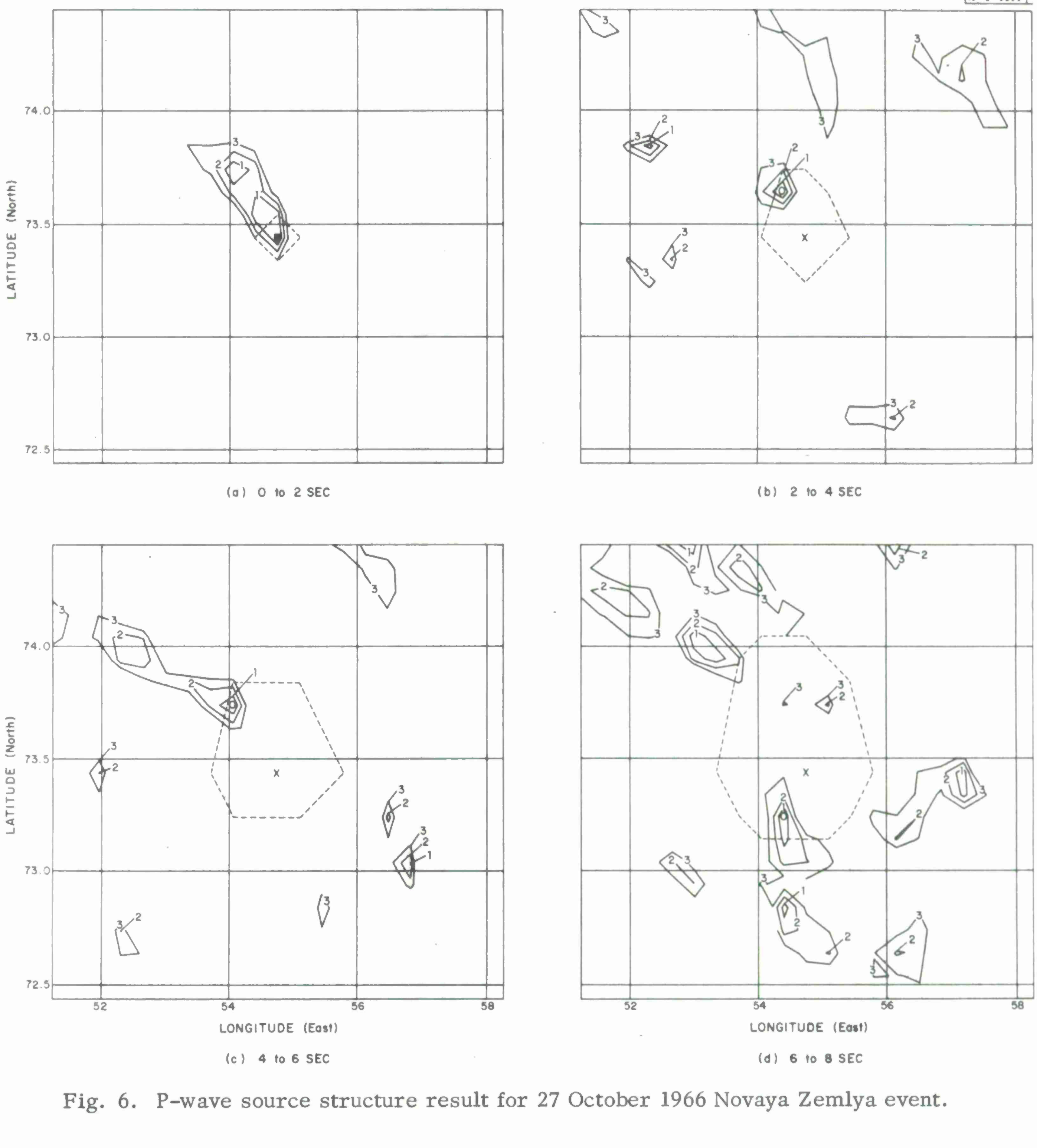

Fig. 6. P-wave source structure result for 27 October 1966 Novaya Zemlya event.

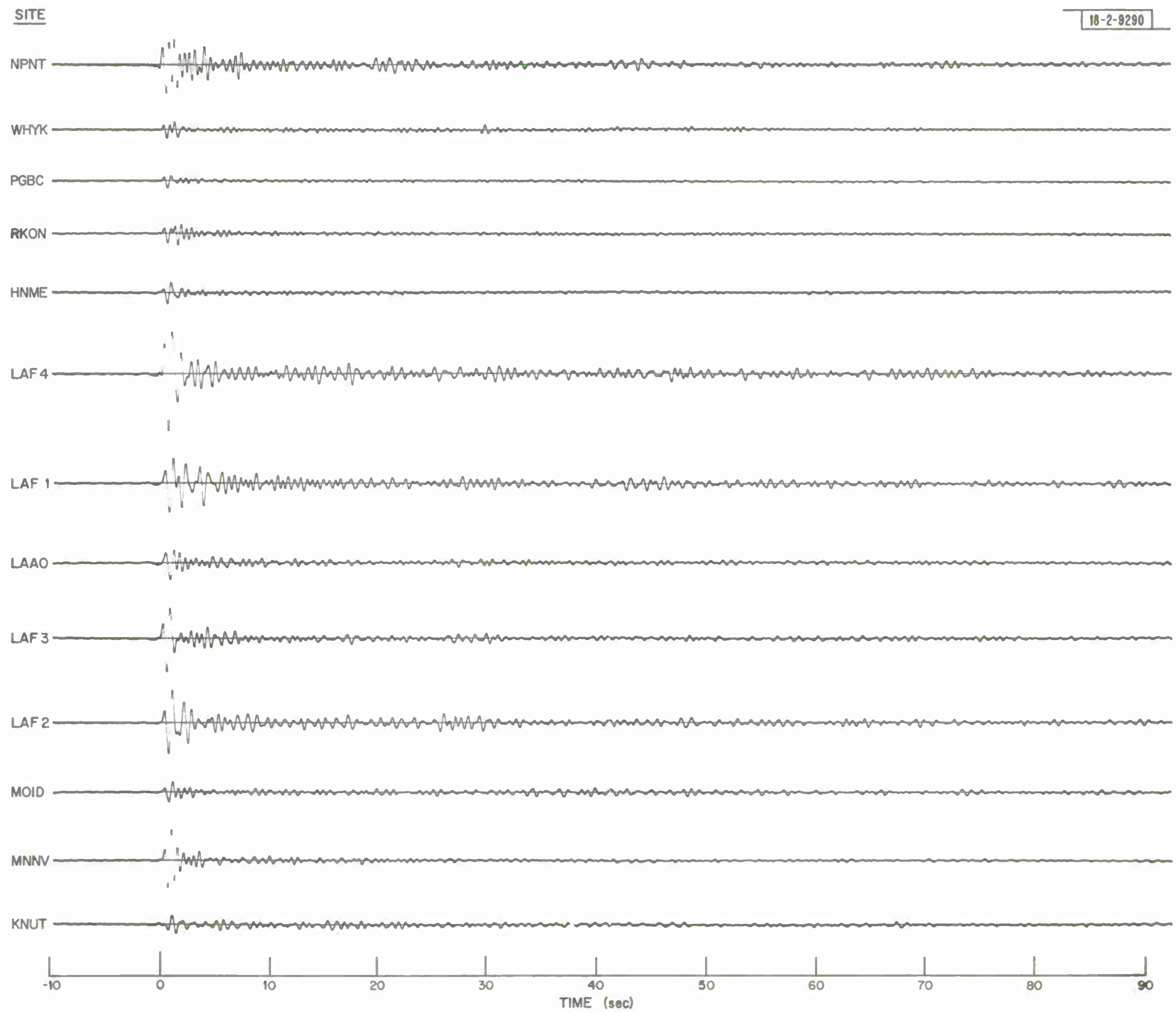

Fig. 7. Waveforms for 18 December 1966 Eastern Kazakh event.

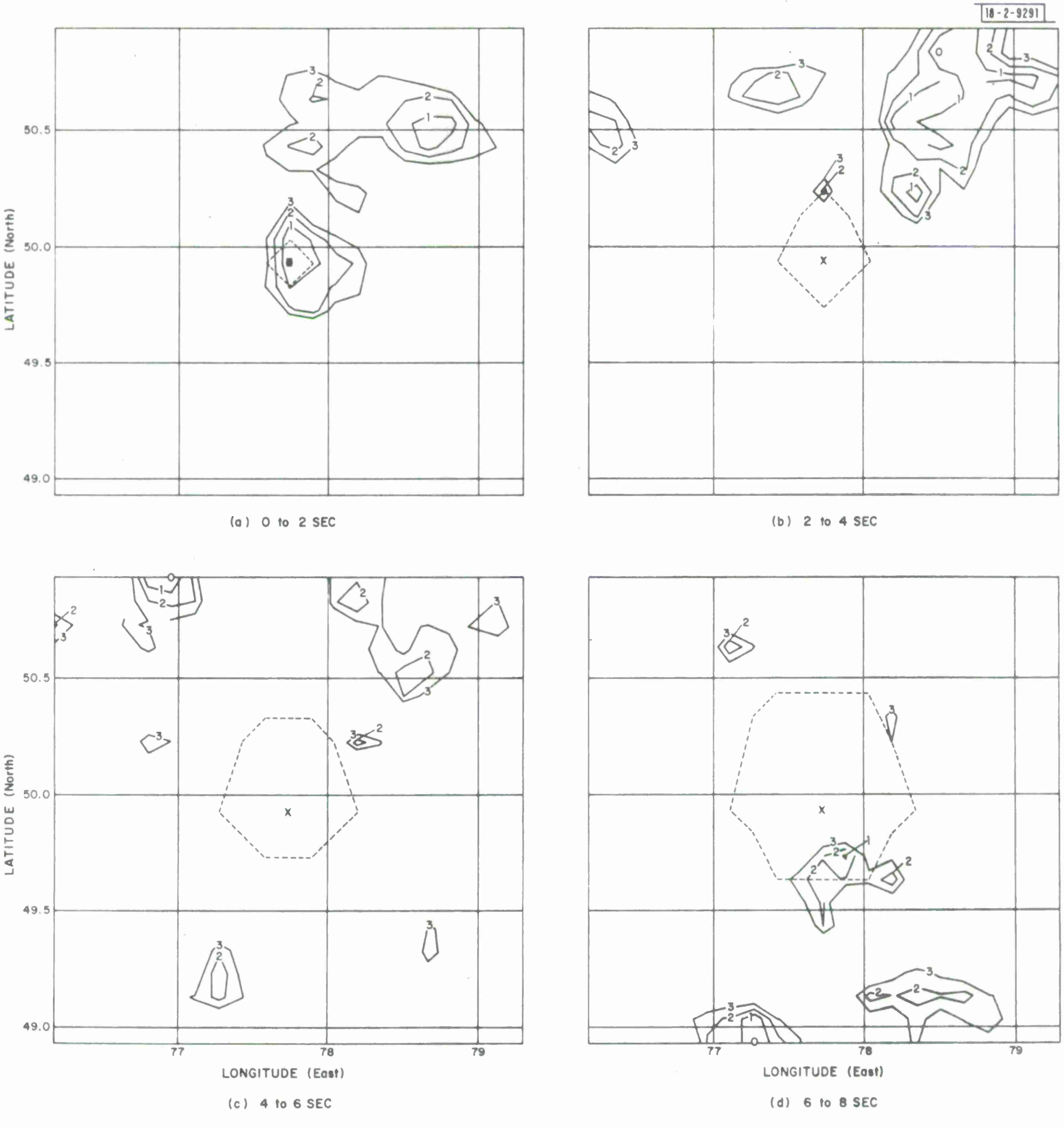

Fig. 8. P-wave source structure result for 18 December 1966 Eastern Kazakh event.

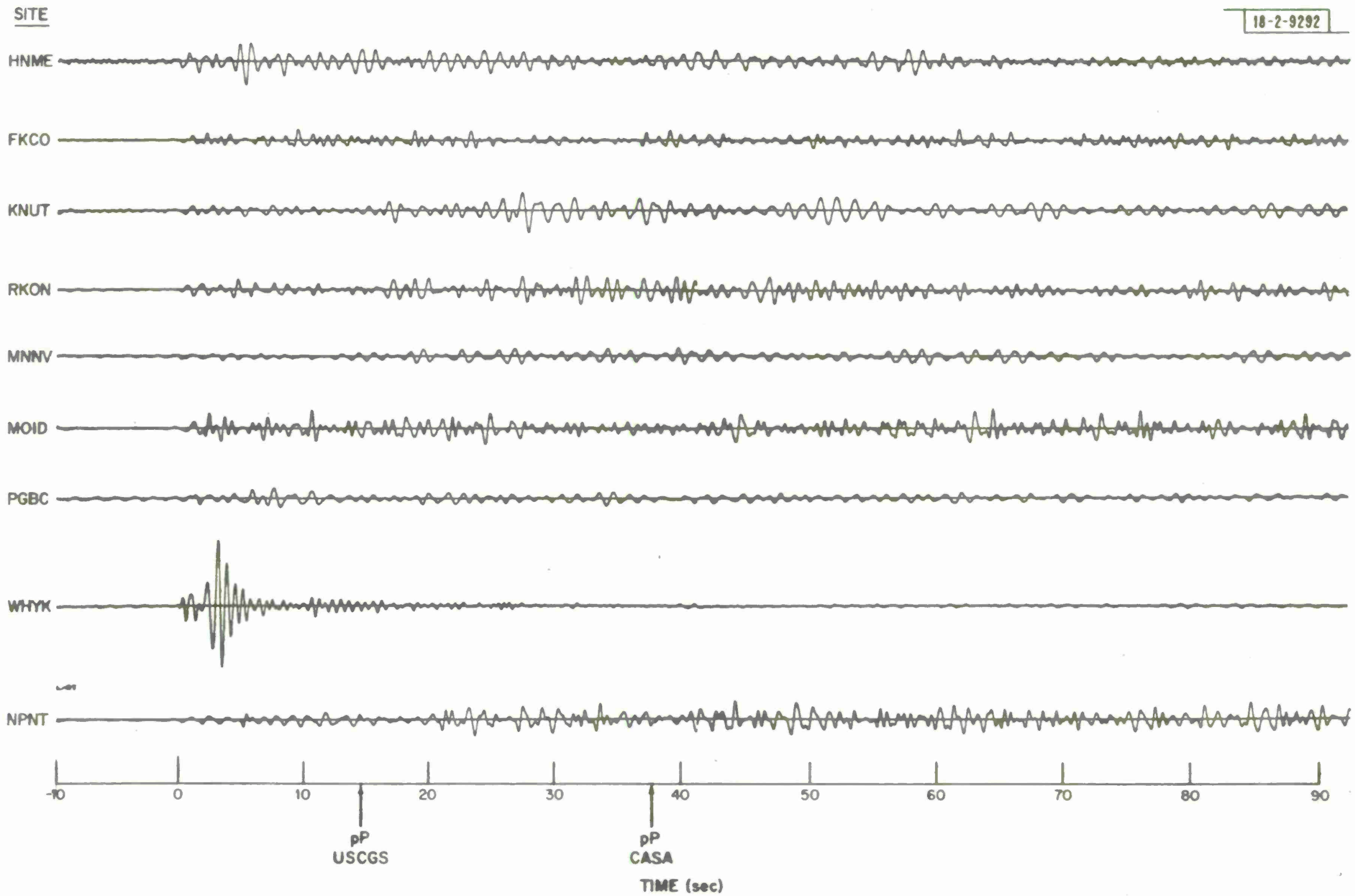

Fig. 9. Waveforms for 9 February 1967 Colombia event.

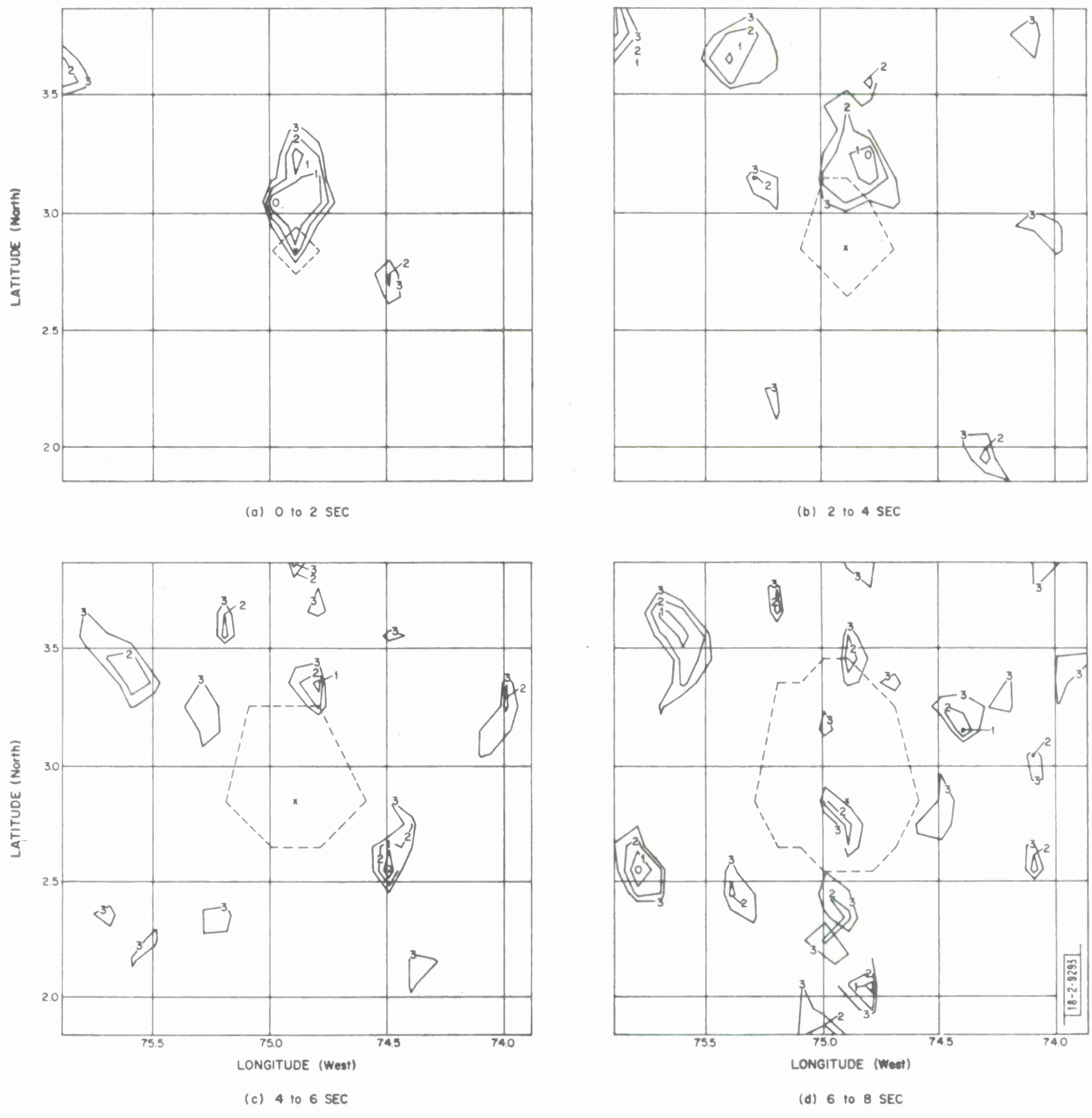

Fig. 10. P-wave source structure result for 9 February 1967 Colombia event.

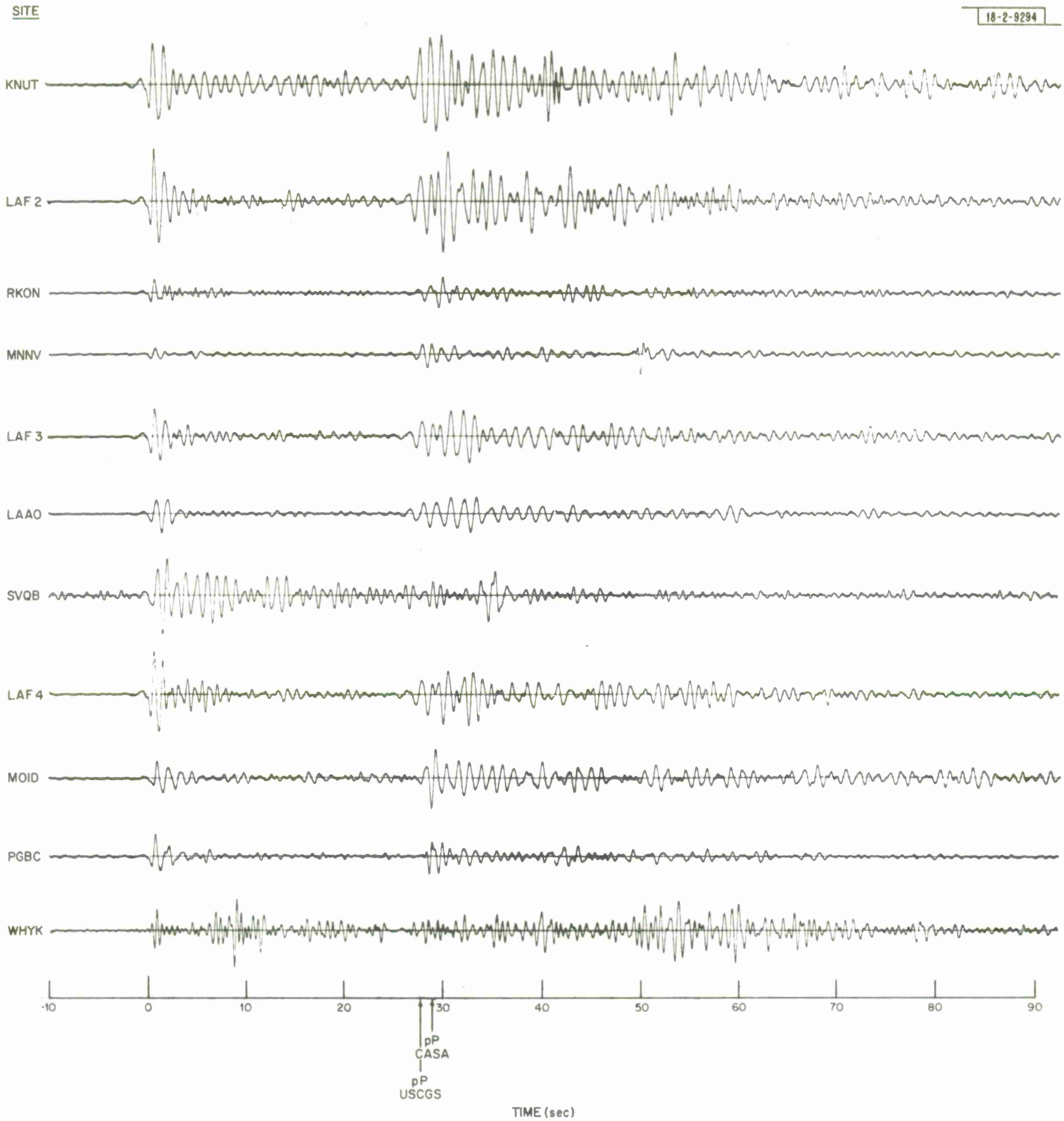

Fig. 11. Waveforms for 14 May 1967 Chile-Bolivia Border Region event.

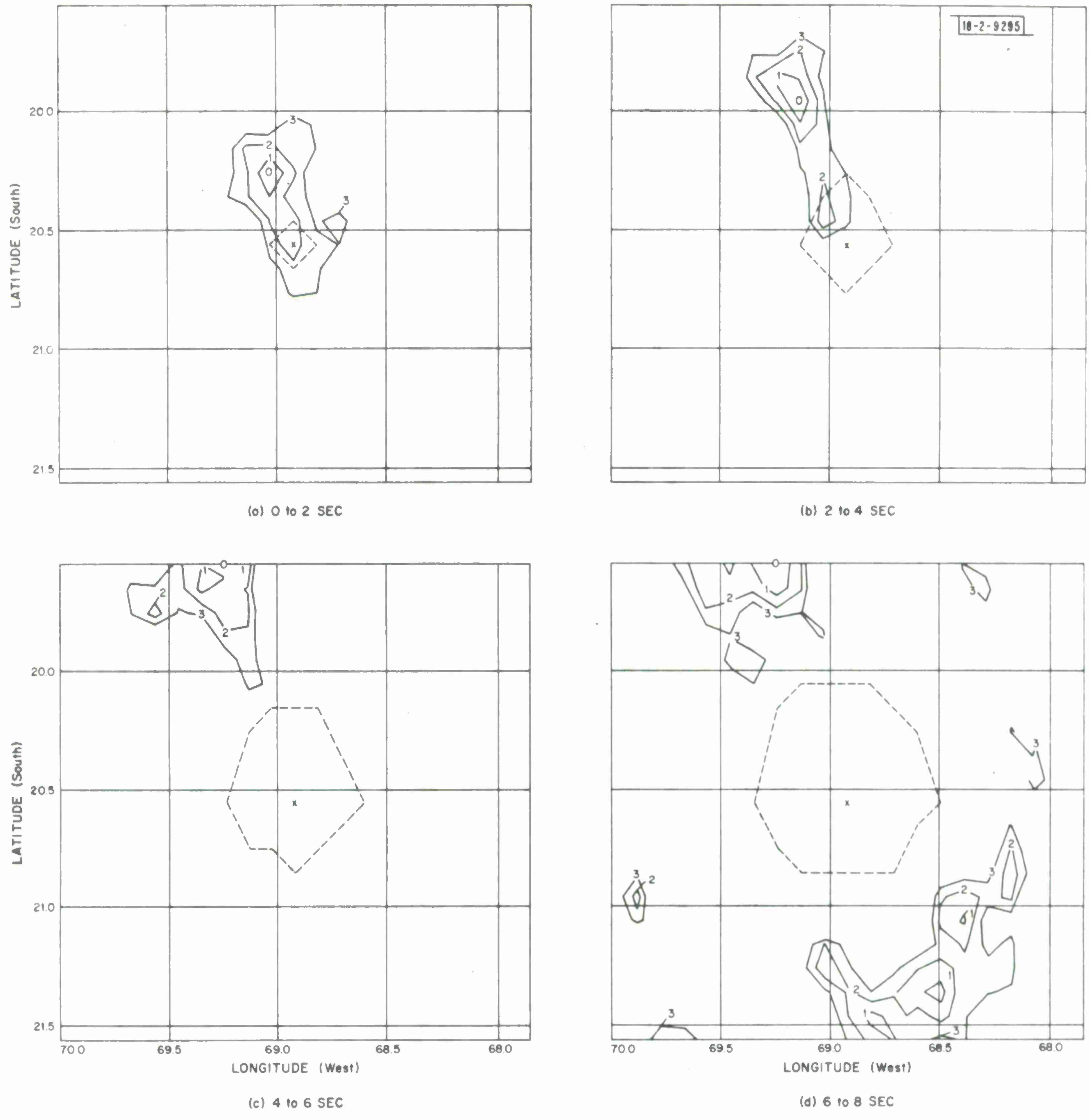

Fig. 12. P-wave source structure result for 14 May 1967 Chile-Bolivia Border Region event.

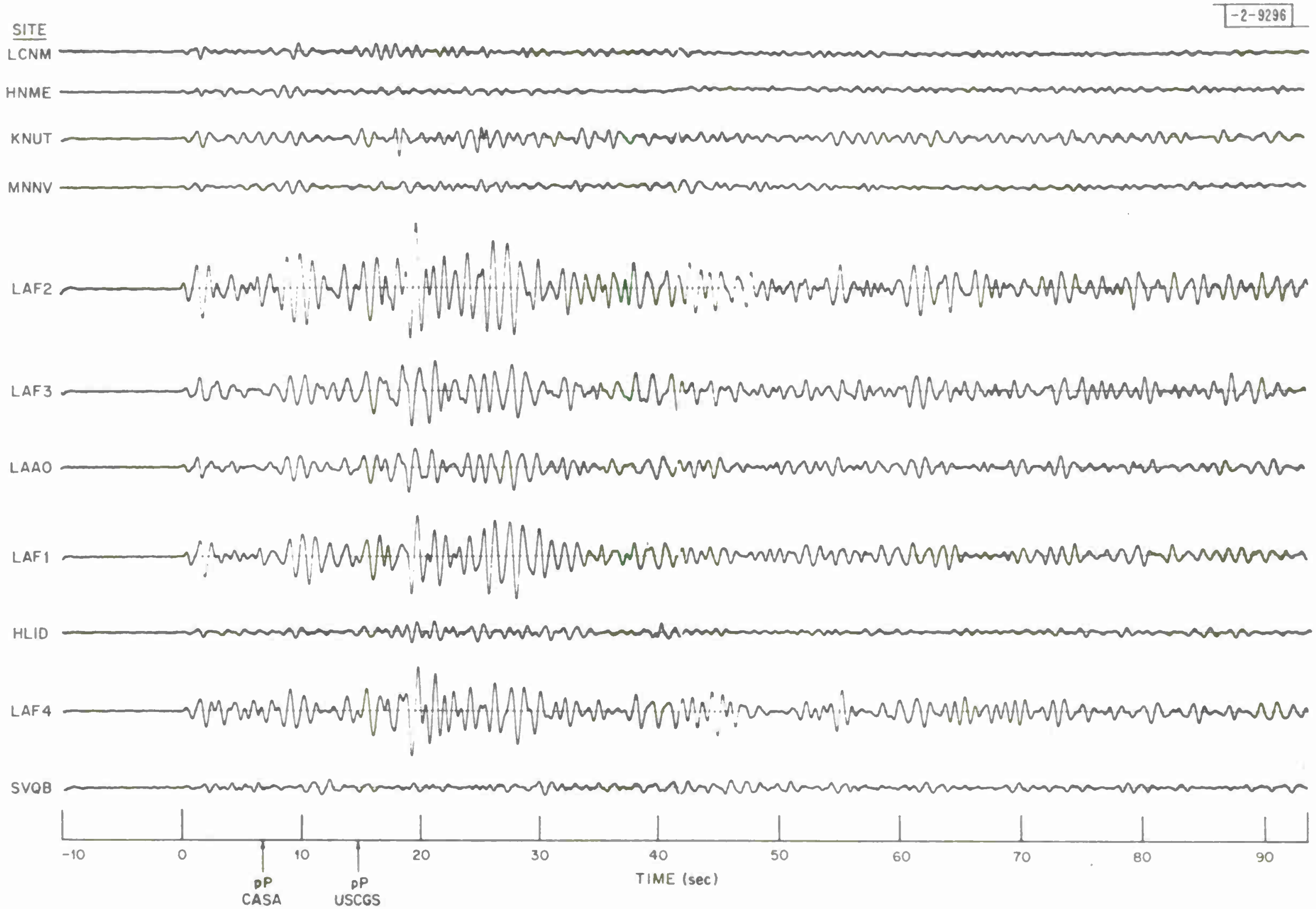

Fig. 13. Waveforms for 26 September 1967 Near Coast of Central Chile event.

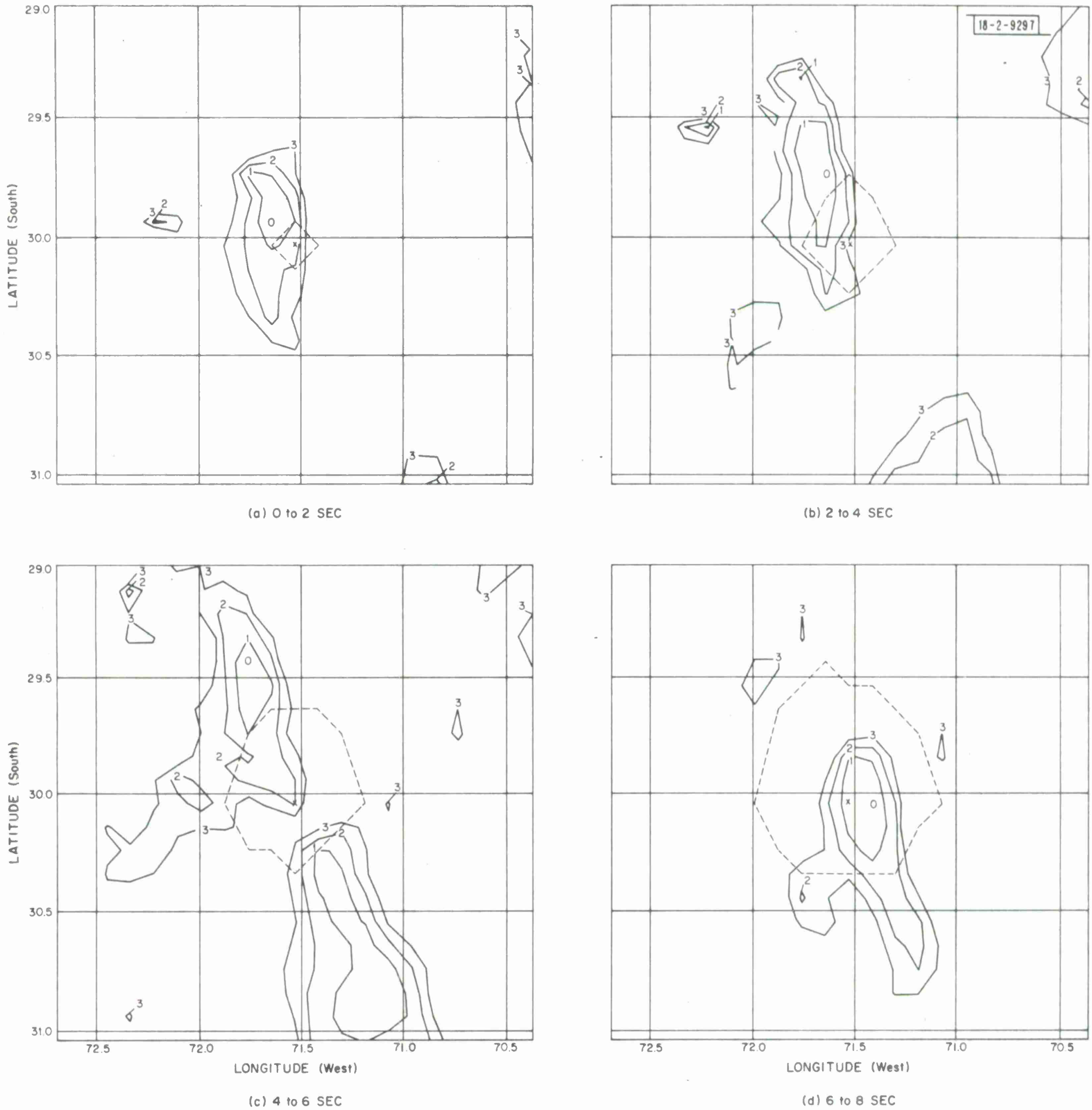

Fig. 14. P-wave source structure result for 26 September 1967 Near Coast of Central Chile event.

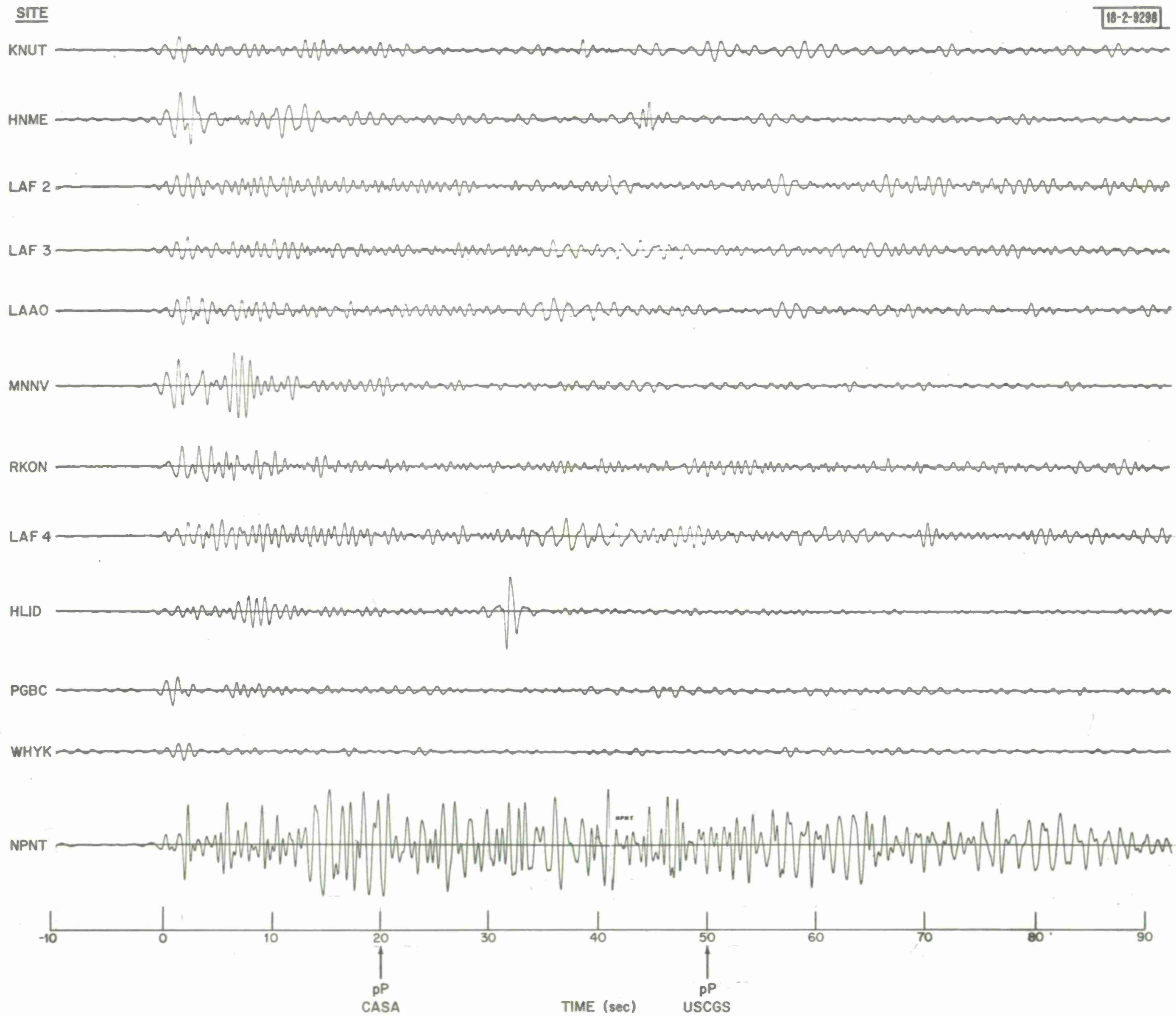

Fig. 15. Waveforms for 15 October 1967 Near Coast of Nicaragua event.

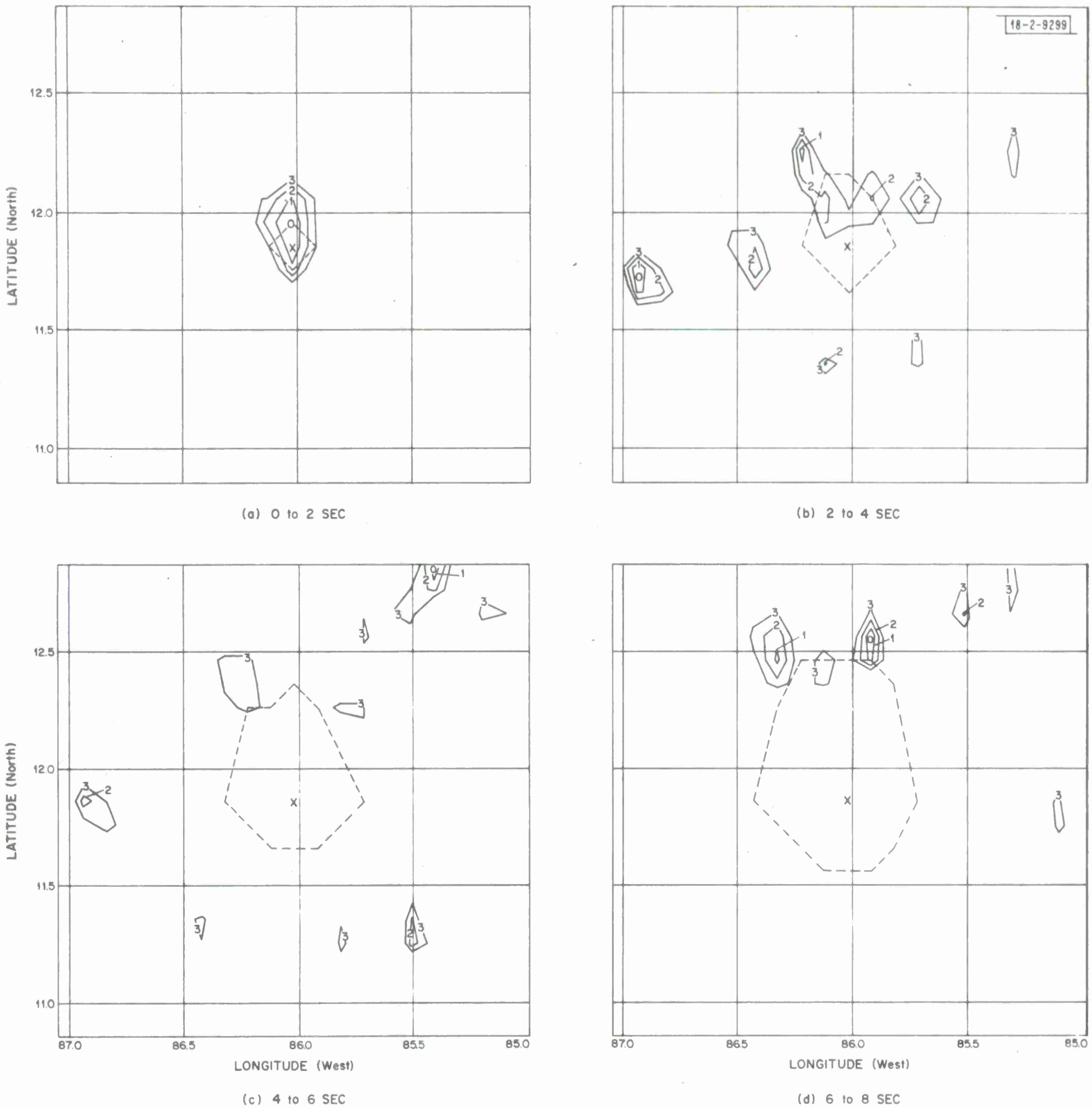

Fig. 16. P-wave source structure result for 15 October 1967 Near Coast of Nicaragua event.

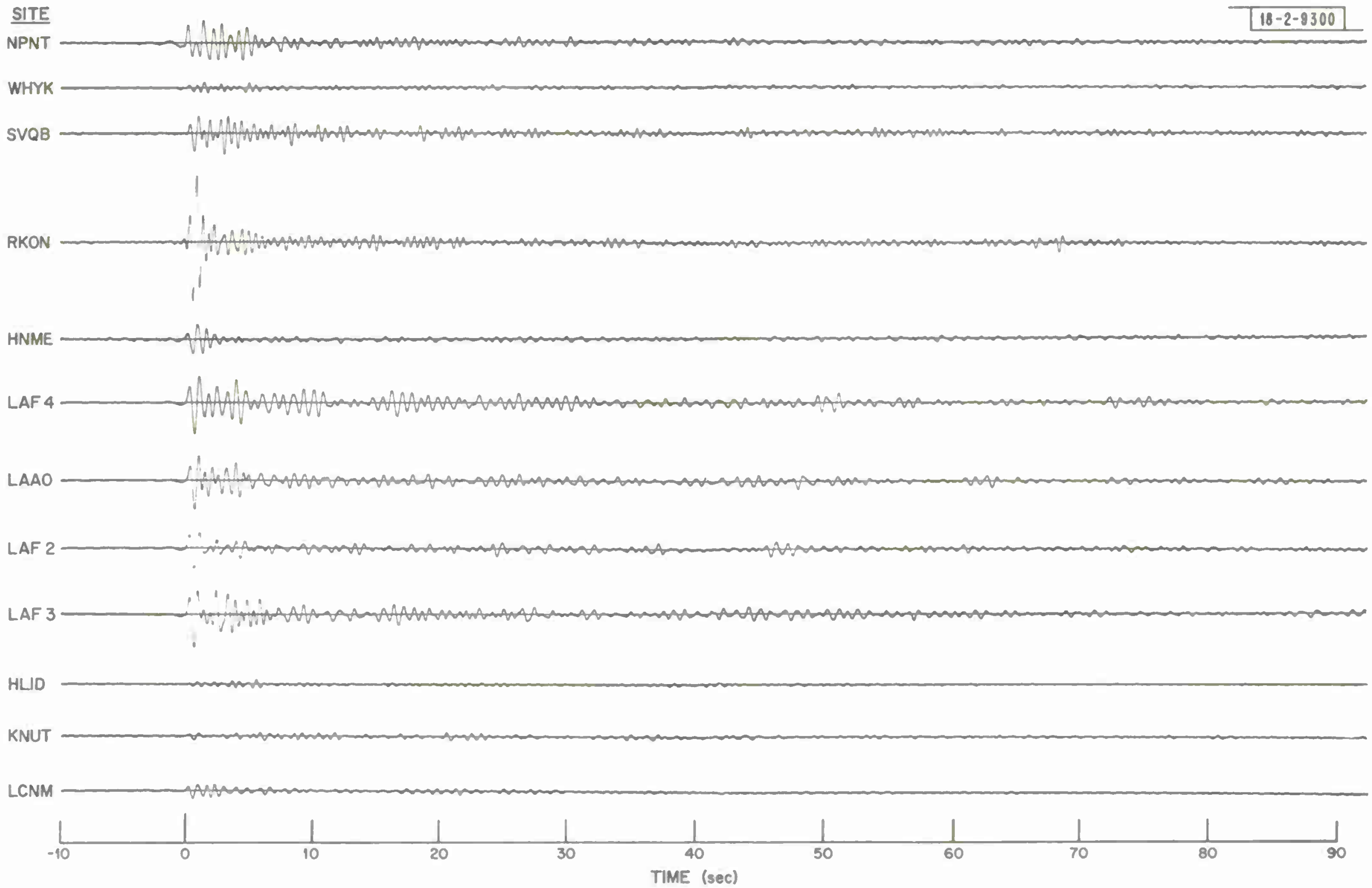

Fig. 17. Waveforms for 21 October 1967 Novaya Zemlya event.

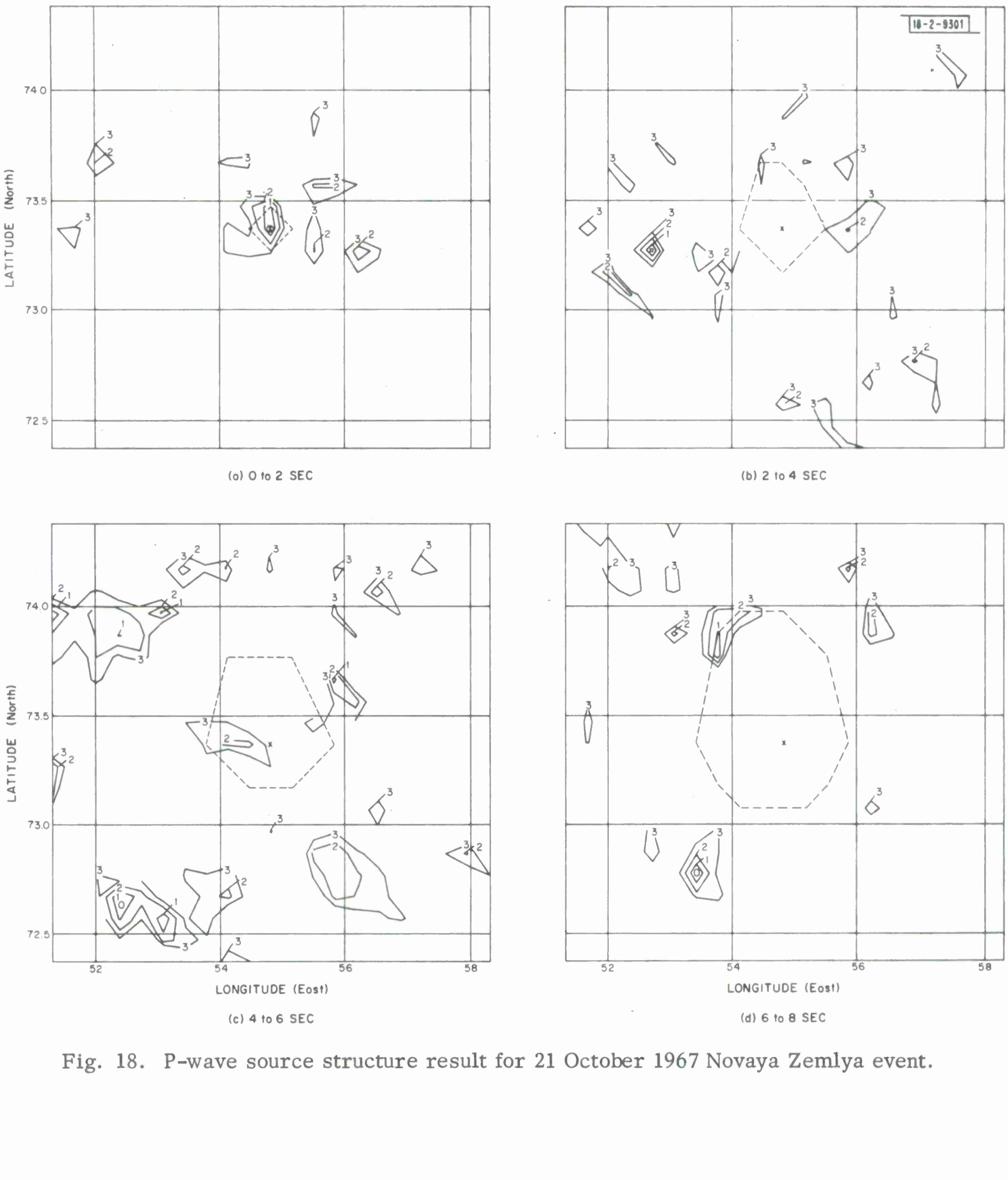

Fig. 18. P-wave source structure result for 21 October 1967 Novaya Zemlya event.

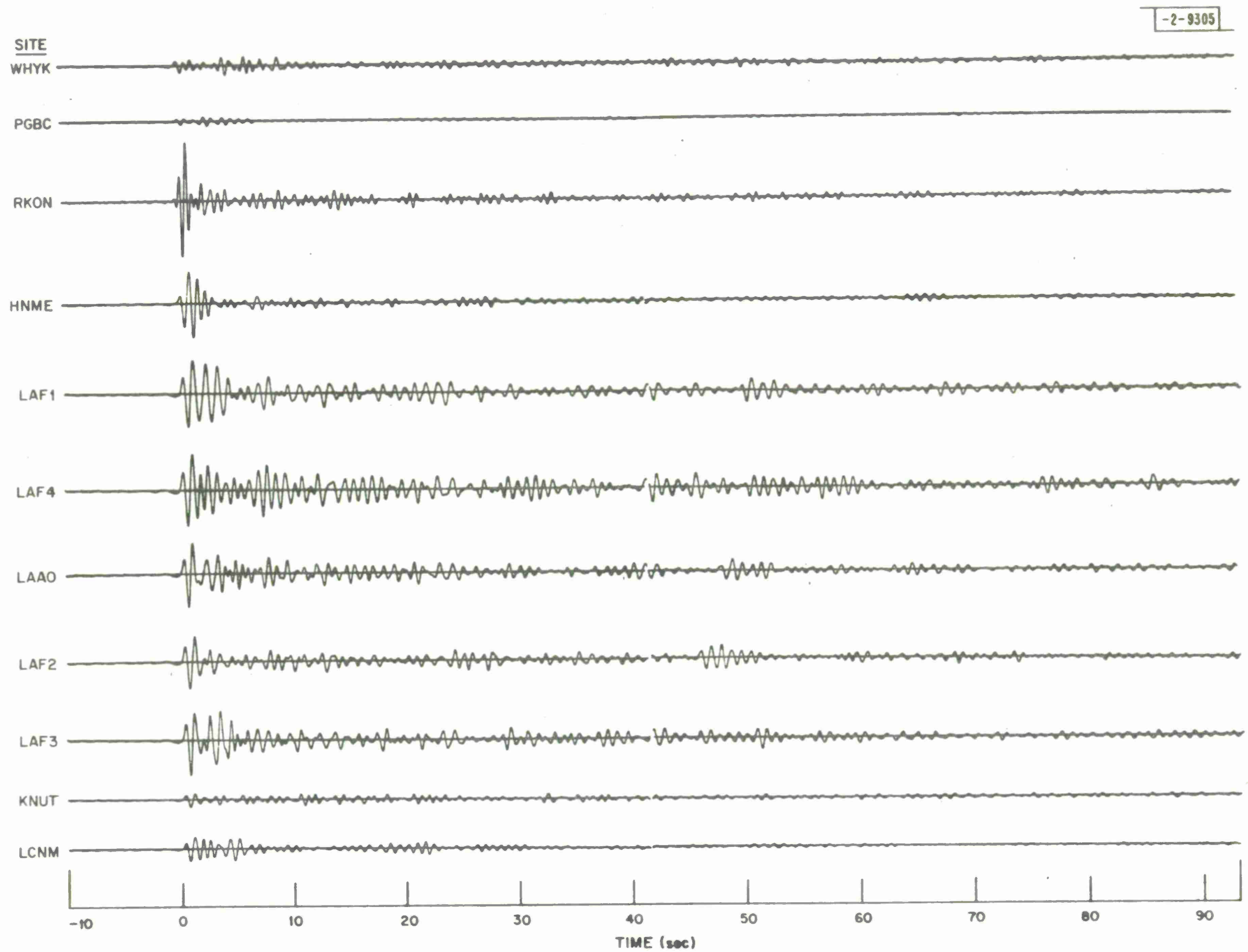

Fig. 19. Waveforms for 7 November 1968 Novaya Zemlya event.

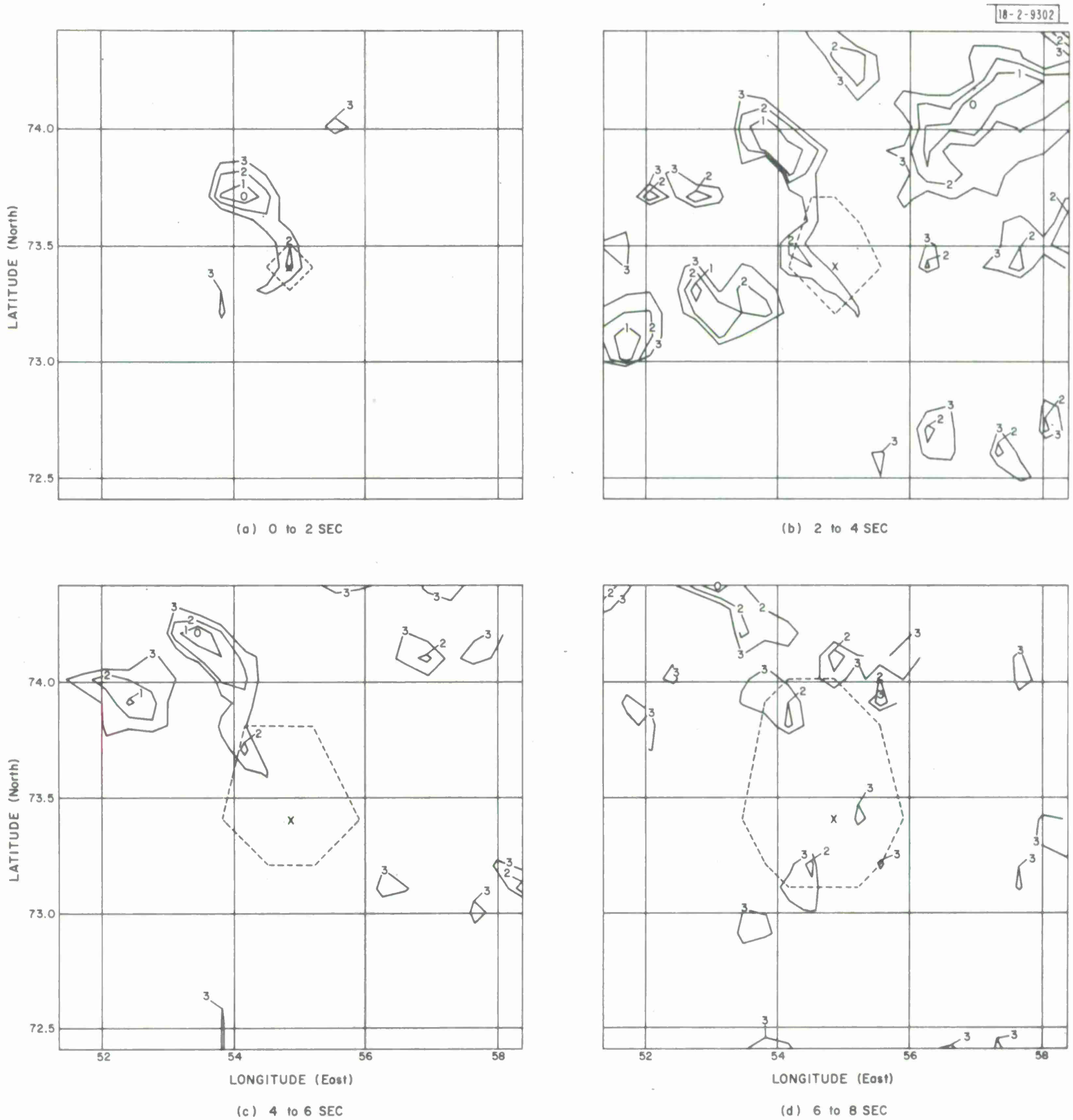

Fig. 20. P-wave source structure result for 7 November 1968 Novaya Zemlya event.

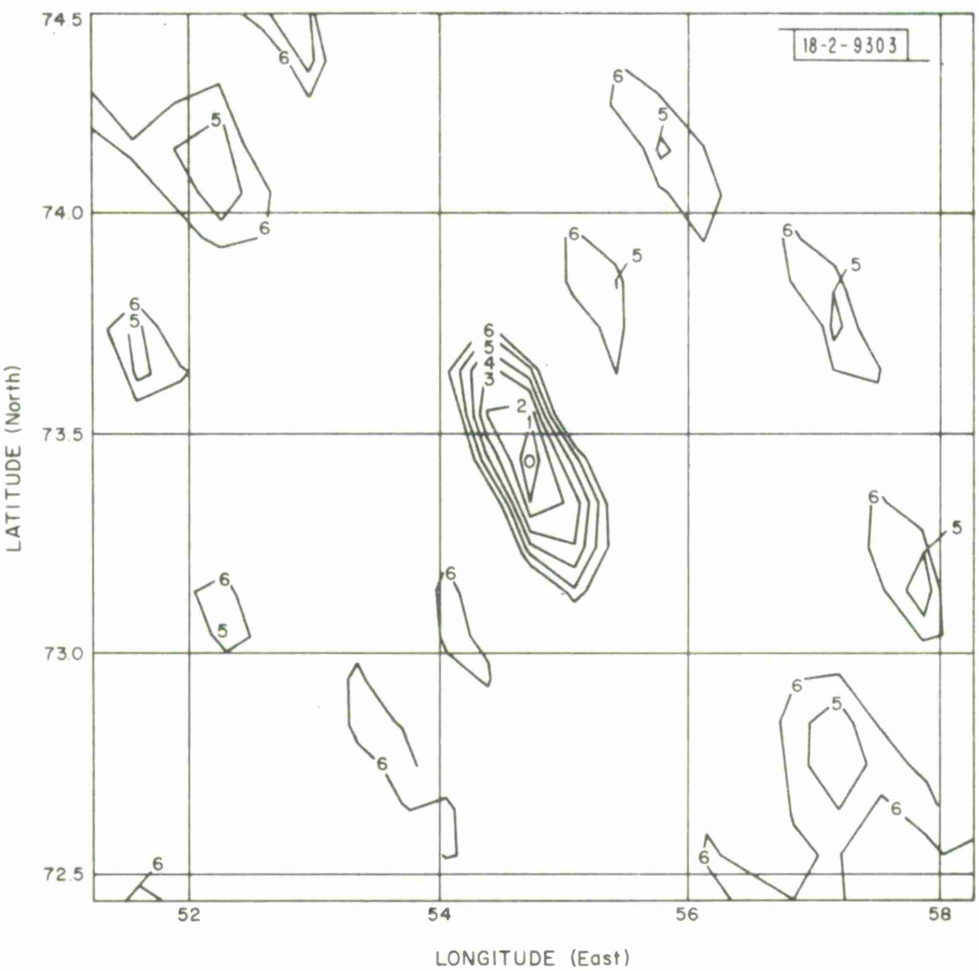

Fig. 21. Typical theoretical network beam pattern at 1 Hz.

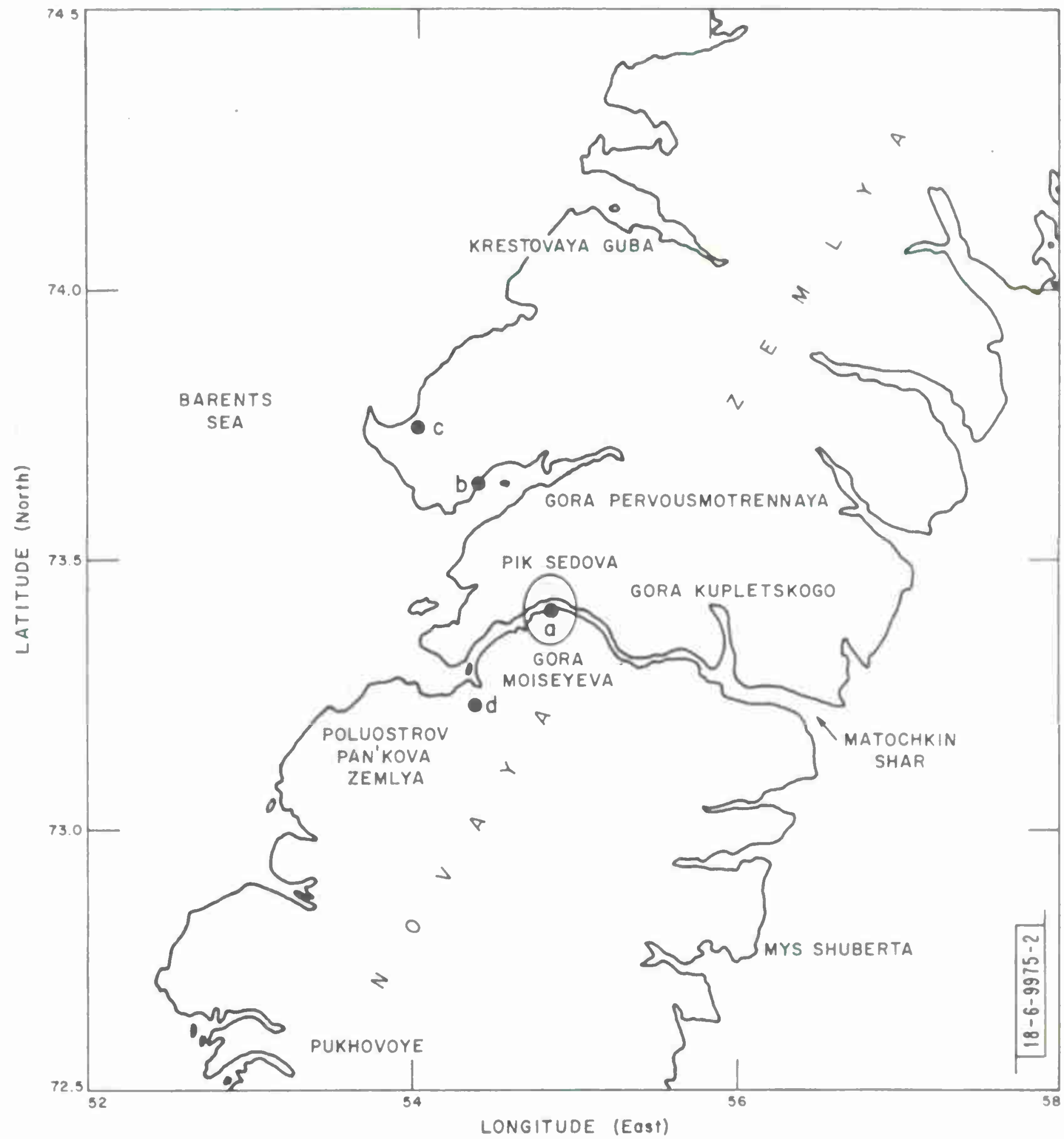

Fig. 22. Migration of location of peak power for 27 October 1966 Novaya Zemlya event.

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13. ABSTRACT

The processing of short-period P-wave data from a continental aperture seismic array is considered. The array consists of sites located at the Large Aperture Seismic Array (LASA) in eastern Montana and Long Range Seismic Measurement (LRSM) stations located in North America. In particular, the feasibility of recognizing the arrival of the pP phase, making use of P-pP differences in velocity across such a large array, is considered. In addition, the determination of the P-wave source structure of an event is considered by using the array to essentially steer many beams in the vicinity of the epicenter of the event. The capability of the array to perform these two functions is evaluated and discussed in detail.

14. KEY WORDS

seismic discrimination	P-wave data	underground explosions
LASA	beamforming	signal processing
LRSM		

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